Correcting DEMs for hydrologic applications: the PEM4PIT model and its parameterization

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1. Introduction

Depressions (Fig. 1a) and flat areas in Digital Elevation Models (DEMs) are considered spurious features that, for hydrological applications, have to be removed from the raw data in order to define the direction of water flow on the surface. Such artifacts can derive by: i) interpolation methods used to produce the DEM starting from point data; ii) the truncation of elevation values to switch from real to integer precision; iii) issues related to indirect methodologies (e.g. air- and spaceborne sensors) adopted to acquire elevation data; iv) the application of the traditional and most diffuses procedures (i.e. *flooding*) able to remove pits but not flat areas: this consists in filling depressions until reaching the elevation of their lowest surrounding, obtaining a flat surface (Fig. 1b). After correcting the DEM the stream network can be extracted using different tecniques (Nardi et al., 2008).
The main drawback of the common correction procedure is that it simulates an irrealistic channel network composed by straight and parallel stream links (Fig. 1c).

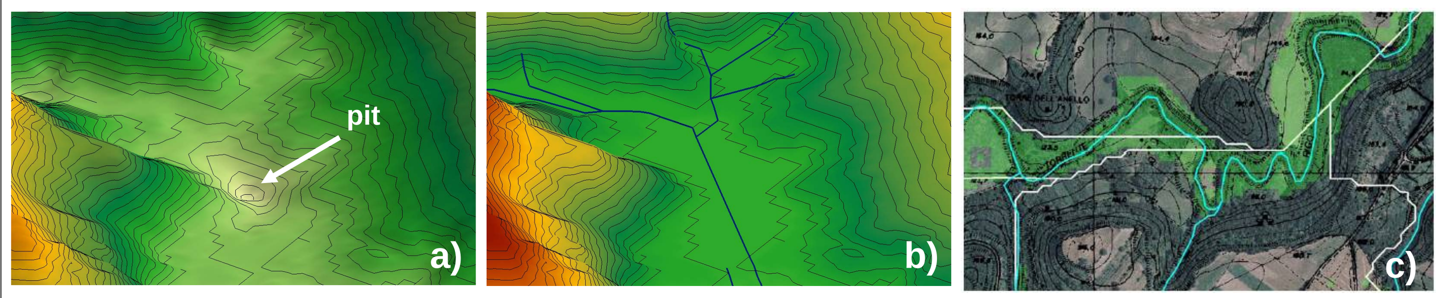


Fig. 1 – a) Example of pit; b) Correction of the pit in a) by the standard flooding procedure and extraction of the stream network; c) Comparison between the simulated stream network by flooding (white line) and the true one (blue line) (Nardi et al., 2008).

Despite *flooding* procedures resolve and eliminate pits, allowing the flow direction delineation according to the Jenson and Domingue's algorithm (1988), nevertheless a lot of uncertaintes arise in selecting the flow direction inside flat spots because of their strong increase after *flooding*.

Basin (m)	Source	Resolution (m)	Precision	Area (km^2)	Pit (%)	(%) flat areas before *flooding*	(%) flat areas after *flooding*
Montana	NED	30	Float	83.62	2.86	0.48	12.15
Naja	IGMI	20	Integer	12.01	0.16	5.97	10.49
Ortacesus	IGMI	25	Float	210.53	0.17	7.09	9.66
Padru	IGMI	25	Float	78	0.14	2	3.88
Pastena	IGMI	40	Integer	40.91	0.12	3.42	20.54
Terranova	IGMI	30	Integer	37.61	0.07	0.91	3.42
Torres	IGMI	25	Float	44.22	0.12	13.84	16.73
Tuscania	IGMI	20	Integer	24.14	0.15	36.93	40.42
Vernon	NED	30	Float	264.95	1.09	2.7	6.32

Tab. 1 - Basins analized by Nardi et al. (2008) and their occurring of spurious features.

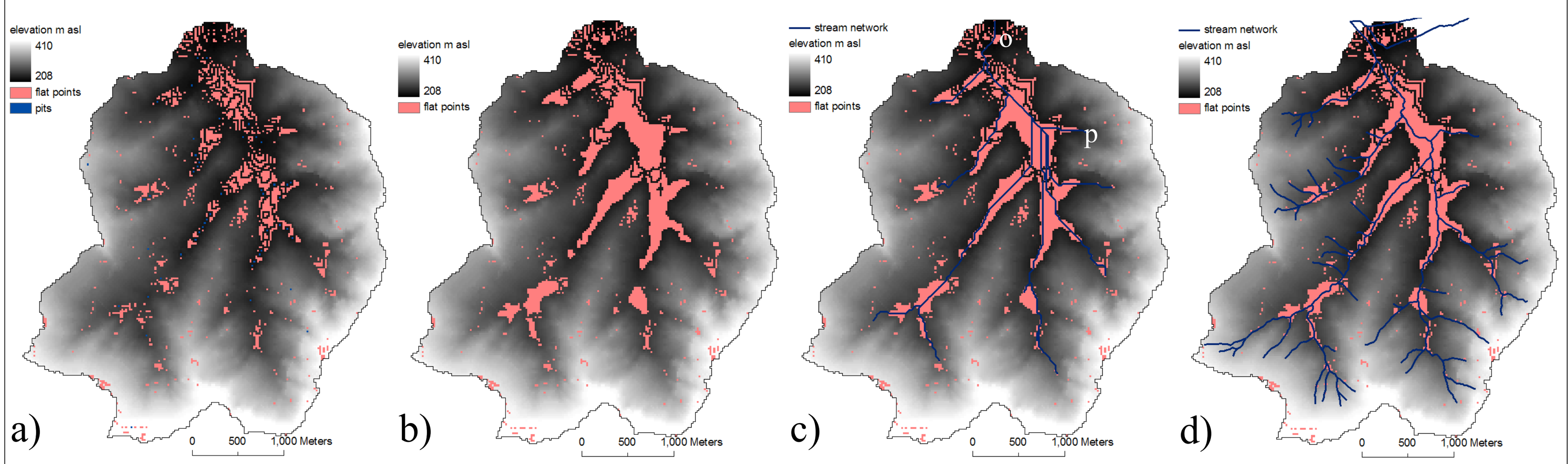


Fig. 2 - a) Distribution of pits (0.16%) and flat areas (5.97%) for the raw DEM of Naja basin (Italy); b) distribution of flat areas (10.49%) over the same DEM after applying the flooding procedure; c) stream network extracted after delineating flow direction by Jenson & Domingue's (1988) approach; d) true stream network obtained by digitizing topographic map at scale 1:25000.

2. The PEM4PIT

The PEM4PIT (Physical Erosion Model for PIT and flat areas correction, Grimaldi et al., 2007) was recently introduced to resolve the pit/flat area issue. It simulates the topographic surface evolution assuming the equilibrium between the tectonic uplift and the sediment flows produced by fluvial erosion and overland diffusion, using the following equation:

$$0 = U - k_e A^{\theta}\left(\frac{z - z_d}{\Delta l}\right) + \frac{4k_d}{\Delta x^2}\left(\breve{z} - z\right) \qquad (1)$$

U [LT^{-1}] is the tectonic uplift
k_e [L$^{1-2\theta}$/T] is the soil erodibility
A [L^2] is the contributing area of the considered DEM cell
z [L] is the elevation of the considered DEM cell
z_d [L] is the elevation of the downstream cell
Δl [L] is the horizontal distance between z and z_d cells
θ is the exponent of the slope-area relationship (0.2-0.7)
k_d [L^{2}T] is the diffusivity coefficient
$\breve{z}$ [L] is the average among the elevations of its four adjacent cardinal cells
Δx is the cell resolution

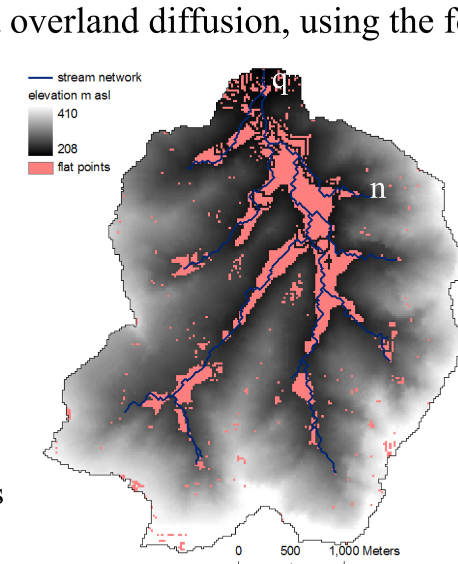


Fig. 3 - Stream network extracted after applying PEM4PIT and delineating flow direction by D8 scheme from the O'Callaghan & Mark's (1984) approach over the same DEM than in Fig. 2.

PEM4PIT starts from Eq.(1), normalizing it by U (tectonic uplift is considered spatially invariant at the basin scale), to correct iteratively all the points with null or negative slope. Eq.(1) becomes:

$$z = \frac{1 + \frac{\beta A^{\theta}}{\Delta l} z_d + \frac{4D}{\Delta x^2}\bar{z}}{\frac{\beta A^{\theta}}{\Delta l} + \frac{4D}{\Delta x^2}} \qquad (2)$$

$\beta = k_e/U$
$D = k_d/U$

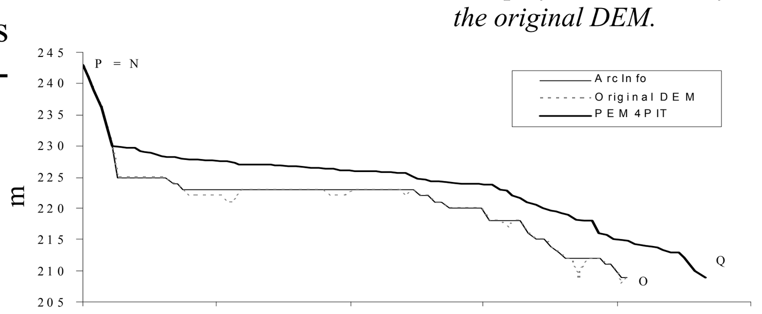


Fig. 4 - Altimetric profiles of the links P-O (Fig. 2c) and N-Q (Fig. 3) as compared to the profile extracted from the original DEM.

3. The flat area issue

In order to assess the terrain analysis procedure which performs better in correcting DEM and representing the stream network in terms of metrics and geometry, Nardi et al. (2008) carried out a deep study focused on flat spots. Different combinations of DEM correction techniques (DEMCM) and single flow direction (SFD) delineation methods were considered.

Basin	DEMCM / SFD	J&D D8	Orl O&M-D8	Orl D8-LTD	Orl Rho8	G&M O&M-D8	G&M D8-LTD	G&M Rho8	PEM4PIT O&M-D8	PEM4PIT D8-LTD	PEM4PIT Rho8	Digitized
MONTANA	Count	43	66	68	67	64	67	59	98	100	98	100
	Dd	2.24	1.97	1.97	1.97	1.95	1.98	1.93	2.2	2.2	2.2	2.42
	Max	840	424.3	424.3	424.3	212.1	212.1	212.1	212.1	212.1	212.1	240
	Mean	131.9	75.3	73.3	74.4	77	74.8	82.7	56.8	55.6	56.8	61.1
	SD	166.3	77.1	73	75.2	49.9	47.6	48.5	40.7	38.8	40.7	44.7
NAJA	Count	37	54	53	53	52	49	49	118	121	118	58
	Dd	5.21	4.71	5.02	4.94	4.2	4.15	4.15	6.26	6.18	6.26	3.17
	Max	520	300	300	300	220	220	220	240.4	226.3	240.4	198
	Mean	109.1	67.5	73.4	72.2	62.6	65.6	65.6	41.1	39.4	41.1	42.3
	SD	126.6	68.1	69.9	69.1	51.8	50.8	51.8	35.7	31.1	35.7	40.6
ORTACESUS	Count	62	175	194	179	155	157	147	372	379	363	289
	Dd	1.19	1.29	1.32	1.31	1.18	1.17	1.15	2.34	2.33	2.32	1.89
	Max	1675	548	530.3	654.1	742.5	742.5	742.5	335.9	335.9	335.9	450
	Mean	178.7	68.9	63.5	68.6	71.2	69.6	73	58.7	57.5	59.8	61.3
	SD	351.3	73.1	68.3	76.6	83.3	84.1	86.5	49.3	47.4	49.4	57.2
PADRU	Count	35	128	132	126	58	55	58	142	146	144	150
	Dd	3.03	2.84	2.86	2.78	2.35	2.33	2.35	3.86	3.87	3.91	4.41
	Max	1225	247.5	176.8	176.8	530.3	530.3	530.3	247.5	247.5	212.1	412.5
	Mean	186.6	47.9	46.8	47.6	87.4	91.3	87.6	58.7	56.6	58.7	63.4
	SD	285.8	32.7	28.6	27.1	100.3	109.3	95.8	42.1	40.9	42.5	56.8
PASTENA	Count	13	10	10	10	28	28	24	107	111	122	92
	Dd	1.27	1.28	1.28	1.28	1.24	1.25	1.2	2.38	2.36	2.45	1.82
	Max	1527.3	1583.9	1583.9	1583.9	1244.5	1244.5	1244.5	339.4	339.4	339.4	440
	Mean	418.6	547.4	547.4	547.4	189.8	190.8	214.1	95.2	91.2	86.1	84.8
	SD	478.2	510.1	510.1	510.1	276.7	276.6	293.4	73.4	69.3	66.3	67.9
TERRANOVA	Count	103	101	94	102	122	118	125	178	182	176	168
	Dd	4.39	4.35	4.13	4.09	4.62	4.51	4.58	5.43	5.34	5.21	4.6
	Max	870	870	870	870	381.8	381.8	480	297	300	300	270
	Mean	89	90	91.9	83.9	79.1	80	76.6	63.8	61.3	61.8	57.2
	SD	113.9	115.5	121	114.5	68.4	74	72.7	47.6	49	49.4	41.3
TORRES	Count	98	140	146	141	126	129	125	280	286	275	244
	Dd	4.45	4.25	4.25	4.22	4.08	3.68	3.89	5.71	5.53	5.61	4.89
	Max	1300	575	575	575	353.6	353.6	353.6	282.8	282.8	282.8	353.6
	Mean	114.4	76.5	73.4	75.4	81.6	71.9	78.5	51	48.7	51	50.5
	SD	161.6	88.6	86.4	87.1	71.2	65.3	69.1	36.2	34.3	35.2	37.8
TUSCANIA	Count	53	64	64	60	121	125	119	192	194	190	134
	Dd	1	1.21	1.2	1.2	1.62	1.62	1.54	1.94	1.98	1.93	0.77
	Max	580	367.7	367.7	600	254.6	254.6	254.6	367.7	367.7	367.7	198
	Mean	87.6	87.3	87	92.9	62.2	60.1	59.8	46.9	47.4	47	47.4
	SD	106.1	75.5	75.2	99.3	53.2	52.4	50.2	41.2	41.7	41.2	34.7
VERNON	Count	53	128	126	125	83	86	84	163	168	163	321
	Dd	0.9	0.6	0.6	0.6	0.6	0.61	0.6	0.61	0.61	0.61	1.01
	Max	2475	1187.9	1187.9	1187.9	721.2	721.2	721.2	361.3	339.4	361.3	169.7
	Mean	280.4	77.6	78.7	79.3	119.8	116	118.4	61.6	59.7	61.6	51.8
	SD	456.8	114.5	115.5	115.2	142.5	130.8	142	47.2	45.2	47.2	28.1

***Tab 2** - Quantitative analysis of stream network extracted on flat areas summarizing results in number of links (Count), drainage density (Dd, km/km^2) and statistics (maximun, mean and standard deviation) of link length for the nine study basins.*

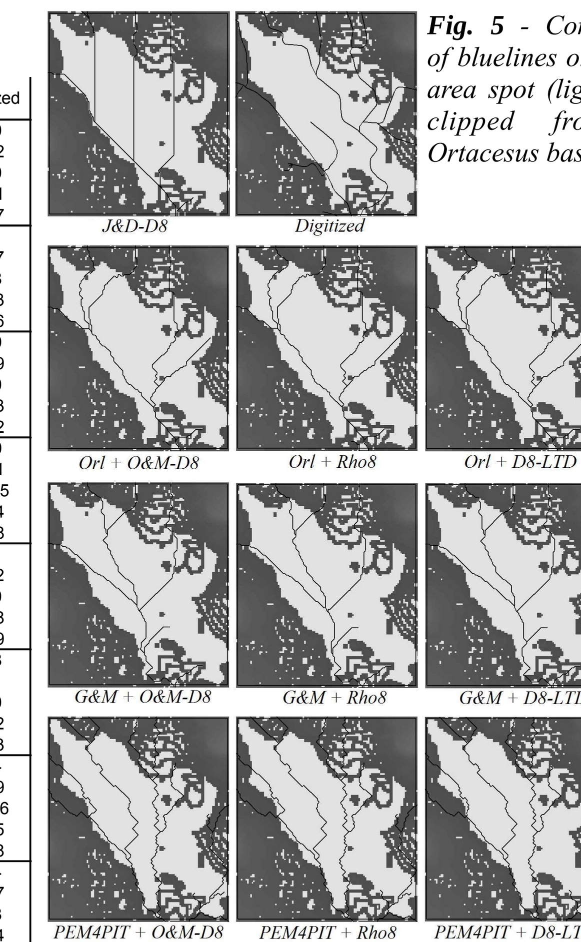


***Fig. 5** - Comparison of bluelines on the flat area spot (light grey), clipped from the Ortacesus basin.*

J&D-D8: D8 by Jenson and Domingue (1988)
Orl: DEM correction by Orlandini et al. (2003)
G&M: DEM correction by Garbrecht & Martz (1997)
PEM4PIT: DEM correction by Grimaldi et al. (2007)
O&M-D8: D8 by O'Callaghan & Mark (1984)
Rho8: Random D8 by Fairfield & Leimarie (1991)
D8-LTD: D8 by Orlandini et al. (2003)
Digitized: digitized blueline

4. The estimate of β and D

Despite PEM4PIT proved to be more suitable than commonly used geometric methods to reconstruct hydrologically connected topography and reliable stream network metrics, fundamental in rainfall/runoff modeling, the best choice of the three model parameters (D, β, θ) remained an open issue to be investigated. An effort was made by Santini et al. (in review) on several ASTER DEMs to supply the PEM4PIT of a parameter estimation procedure based on following assumptions: the diffusive component of surface evolution dominates on hillslopes; the fluvial one in accumulation areas; in transitional areas the two components may combine.

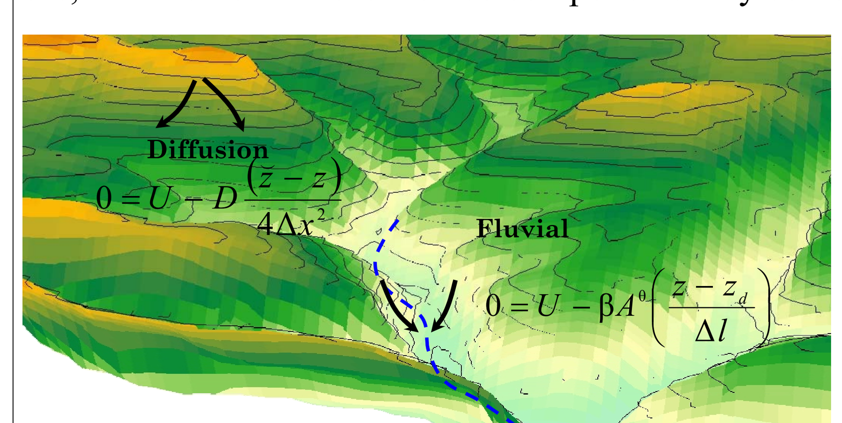


Fig. 6

Considering to partially apply the model in Eq. (2) as in the left Fig. 6 for the respective domains, it is possible to estimate:

$$D = -\frac{U \cdot \Delta x^2}{4 \cdot (\bar{z} - z)} \qquad (3) \qquad\qquad \beta = \frac{U \cdot \Delta l}{A^{\theta} \cdot (z - z_d)} \qquad (4)$$

For β estimation, three typical values of θ (0.3, 0.4, 0.5) were assumed. Then average values for each parameter are computed and used in PEM4PIT.

basin	total n. of cells	mean D	n. cells for D estimation	$\theta = 0.3$ mean β	$\theta = 0.4$ mean β	$\theta = 0.5$ mean β	n. cells for β estimation
ast03	114.21	257	27.39	0.20	0.06	0.02	3.04
ast07	22.59	246	31.07	0.43	0.13	0.04	3.37
ast10	35.67	275	30.54	0.54	0.17	0.05	4.15
sangi	50.92	251	30.24	0.27	0.08	0.02	4.06
terra	37.61	173	31.12	0.17	0.05	0.01	4.62
as1	131.16	296	25.98	0.27	0.08	0.02	2.86
as2	53.97	277	25.34	0.17	0.04	0.01	2.25
as3	35.15	271	31.13	0.19	0.05	0.01	2.06
as4	63.61	311	24.75	0.33	0.10	0.03	3.45
as5	49.48	275	30.07	0.21	0.05	0.01	1.62

***Tab. 3** - Summary of D and β values (with θ=0.3, 0.4 and 0.5) and number of DEM cells considered for their respective estimation.*

basin	θ=0.3 modified cells %	θ=0.3 mean (m)	θ=0.3 st dev (m)	θ=0.4 modified cells %	θ=0.4 mean (m)	θ=0.4 st dev (m)	θ=0.5 modified cells %	θ=0.5 mean (m)	θ=0.5 st dev (m)
ast03	5.82	0.28	1.33	5.98	0.30	1.42	6.01	0.31	1.45
ast07	23.43	2.48	8.02	24.65	2.79	8.46	23.96	2.61	8.18
ast10	25.76	1.84	3.91	29.46	2.57	4.93	29.71	2.57	4.86
sangi	8.56	0.61	3.02	8.79	0.63	3.01	9.10	0.69	3.22
terra	5.10	1.29	7.90	5.24	1.33	8.00	5.22	1.33	7.99
as1	16.57	1.50	4.65	16.73	1.54	4.74	17.74	1.76	5.14
as2	9.51	0.66	3.01	9.91	0.72	3.15	10.12	0.75	3.26
as3	7.43	0.55	2.46	7.71	0.58	2.55	7.64	0.57	2.46
as4	14.17	0.71	2.28	14.53	0.74	2.36	15.00	0.79	2.43
as5	9.17	0.92	3.77	9.44	0.95	3.80	9.53	1.00	3.99

***Tab. 4** - Impact of PEM4PIT over raw DEMs with the three different sets of estimated parameters by changing θ.*

5. The estimate of θ

After a preliminary stream network extraction by standard procedures (*flooding* + SFD), two methods are tested for θ estimation. ASTER DEMs for four study basins in Basilicata region (Italy) are used as input dataset: AST07, AST10, AST11 and AST12.

Method 1
Horton parameters R_a (area ratio) and R_s (slope ratio) are calculated and used to estimate θ (Flint, 1974).

$$\theta = \frac{\ln R_s}{\ln R_a}$$

	AST07	AST10	AST11	AST12
R_a	5.04	4.35	4.13	4.09
R_s	1.93	1.80	1.89	1.81
θ	0.41	0.40	0.45	0.42
β	0.11	0.17	0.04	0.04
D	368	414	332	326

Method 2
Eq.(1) is a simplified form of detachment-limited erosion model, whose the fluvial term assesses that:

$$S = \left(\frac{U}{k_e}\right)^{1/n} A^{-m/n} \qquad (5) \qquad \text{with} \qquad \frac{m}{n} = \theta$$

Transport-limited (TL) incision can be modeled in a similar fashion, in this case:

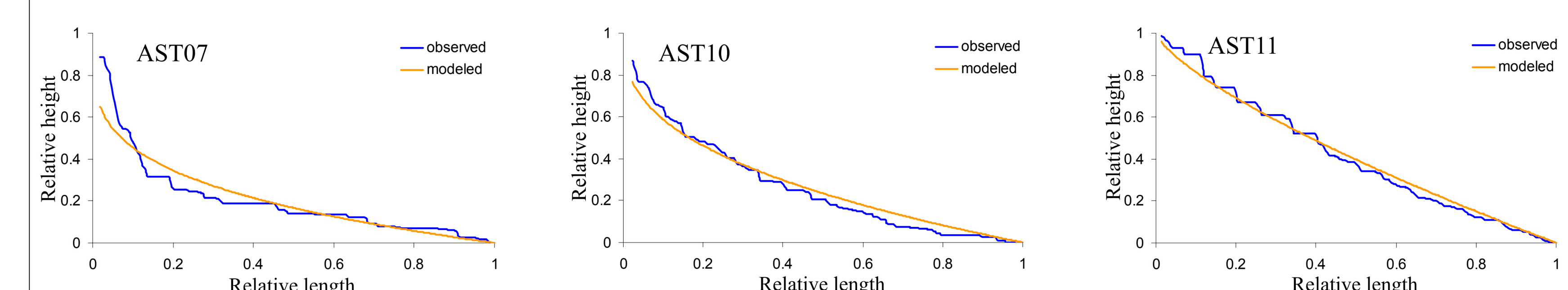
$$S = \left(\frac{U}{\gamma k_t}\right)^{1/n} A^{(1-m)/n} \qquad (6) \qquad \text{with} \qquad \frac{m-1}{n} = \theta$$

γ represents the fraction of eroded material that is transported, k_t is the transport efficiency factor
Kirkby (1971) resolved the continuity equation for fluvial erosion in case of TL as:

$$\frac{y}{y_0} = 1 - \left(\frac{x}{x_1}\right)^{\frac{1-m}{n}+1} \qquad (7)$$

being y/y_0 the relative height and x/x_1 the relative distance from the divide in a river profile

TL conditions can be assumed for the cases under study with a decreasing strength from AST07 to AST10 to AST11 to AST12 because of the decreasing average thickness of loose material covering the basin surface. The longest river channels for each basin are considered here to invert the model in eq. (7) in order to derive m and n.



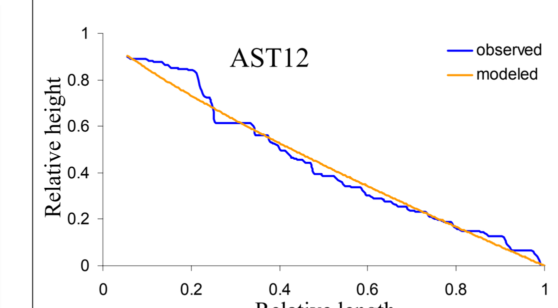


Fig. 7 - Comparison between observed river profiles and the ones modeled after estimating m and n

	AST07	AST10	AST11	AST12
m	2.483	2.416	1.251	1.207
n	2.013	2.304	0.929	1.141
θ	0.74	0.61	0.27	0.18
β	0.01	0.01	0.38	1.02
D	368	414	332	326

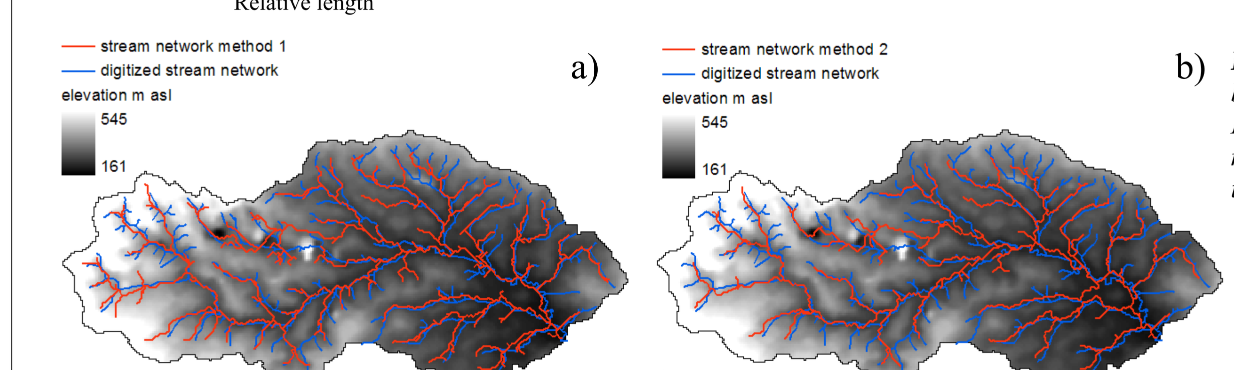


Fig. 8 - Comparison between observed blueline and the ones derived after estimating PEM4PIT parameters for AST07 according to method 1 (a) and method 2 (b) and applying the model.

Tab 5 - Comparison between statistics of distance (in m) from the modeled bluelines and the observed ones digitized at scale 1:50'000.

	AST07 mean	AST07 st dev	AST10 mean	AST10 st dev	AST11 mean	AST11 st dev	AST12 mean	AST12 st dev
method 1	49.19	39.61	161.98	215.36	30.74	31.46	28.15	28.99
method 2	36.49	41.72	161.67	213.35	29.49	30.44	27.92	29.15

6. Conclusions

Compared to other approaches for correcting DEM, PEM4PIT allows to simulate more realistic drainage patterns (in terms of stream network metrics and geometry) and slopes.
For that concerning the model parameterization, the proposed procedure in 4. performs well and its results seem not strongly influenced by θ variation, when this is given *a priori*.
A first attempt to relate the choice of θ to the erosion processes (e.g. transport-limited case) seemed to have better results than using a more generic approach not making such type of distinction: the stream network extracted by method 2 is closer to the true one than for the method 1.
Developing an automatic, more objective and less case-specific algorithm for a physically based parameterization is crucial and requires further case studies and investigations.

Fairfield J. & Leymarie P., 1991. *Water Resour. Res.* 27, 709–717.
Garbrecht J. & Martz L.W., 1997. *J. Hydrol* 193, 204–213.
Grimaldi S., Nardi F., Di Benedetto F., Istanbulluoglu E. & Bras R.L., 2007. *Adv. Wat. Res.*, 30, 2151–2158.
Jenson S.K. & Domingue J. O., 1988. *Photogramm. Engng. Remote Sensing* 54, 1593–1600.
Kirkby M.J., 1971. In: Slopes form and process, Institute of British Geographers, Special Publ. n.3
O'Callaghan J.F. & Mark D.M., 1984. *Comput. Vision Graphics Image Processing* 28, 323–344.
Orlandini S., Moretti G., Franchini M., Aldighieri B. & Testa B., 2003. *Water Resour. Res.* 39(6), 1144. doi:10.1029/2002WR001639.
Nardi F., Grimaldi S., Santini M., Petroselli A. & Ubertini L., 2008. *Hydrological Science Journal*, 53(6) , 1176-1193.
Santini M., Grimaldi S. Nardi F., Petroselli A., Rulli M.C., (in review), *Geomorphology* (Special Issue).